Comparing the moisture permeability of limecrete and concrete floor slabs

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Abstract

Retrofitting impermeable ground-bearing floor slabs to an old building is thought to 'drive' soil moisture up adjoining walls. Historic England has commissioned the University of Bath to conduct research into water vapour and liquid permeation through typical floor slab materials, and their influence on local soil moisture. The project comprises computer modelling to examine the response of soil moisture to slab installation, laboratory tests to analyse moisture movement rates through slab materials, and field monitoring to measure the effect of different slab materials *in situ*. Initial laboratory tests on two materials, concrete and NHL5-based limecrete, used a bespoke modular soil-slab-air apparatus developed to establish evaporation rates through slab materials. Subsequent material characterisation tests were conducted to compare their microstructural properties and moisture transfer characteristics including mercury intrusion porosimetry (MIP), sorptivity tests, and scanning electron microscopy (SEM). Preliminary results showed the NHL5-based limecrete slab was only marginally more permeable than the concrete slab, suggesting that a NHL5-based limecrete slab might be more effective than a concrete slab in reducing water rise in a wall. Further testing of limecrete mixes and *in situ* monitoring is proposed to verify these results.

Introduction

Moisture is a major cause of deterioration of historic building fabric. It drives many deleterious processes including biological growth, the actions of soluble salts, chemical attack and freeze-thaw damage (Cultrone et al. 2007; Feilden 2003a). Therefore, understanding moisture movement and the factors affecting it are important considerations in building conservation. The sketch in Figure 1 shows the main sources and pathways of moisture in and around a building of traditional construction. Internal sources, such as condensation and leaks, can be controlled by regular maintenance, adequate heating, and ventilation (Feilden 2003b). External water sources including precipitation and wind driven rain can be controlled by creating a water shedding building envelope. But a more discreet and equally important external water source is soil moisture. Although soil moisture levels are influenced by the hydrological characteristics of the site, defective drains and inadequate surface water disposal arrangements often prove to be significant sources. In modern buildings damp proof courses (DPCs) are used to control the capillary rise of moisture in walls, but historic buildings rely on the ability of permeable building fabric to absorb and readily allow evaporation of moisture (Douglas 1998). Therefore, any alterations that might affect the 'hygric balance' (water in = water out) of the building, such as the introduction of a concrete ground-bearing floor slab, require careful consideration.

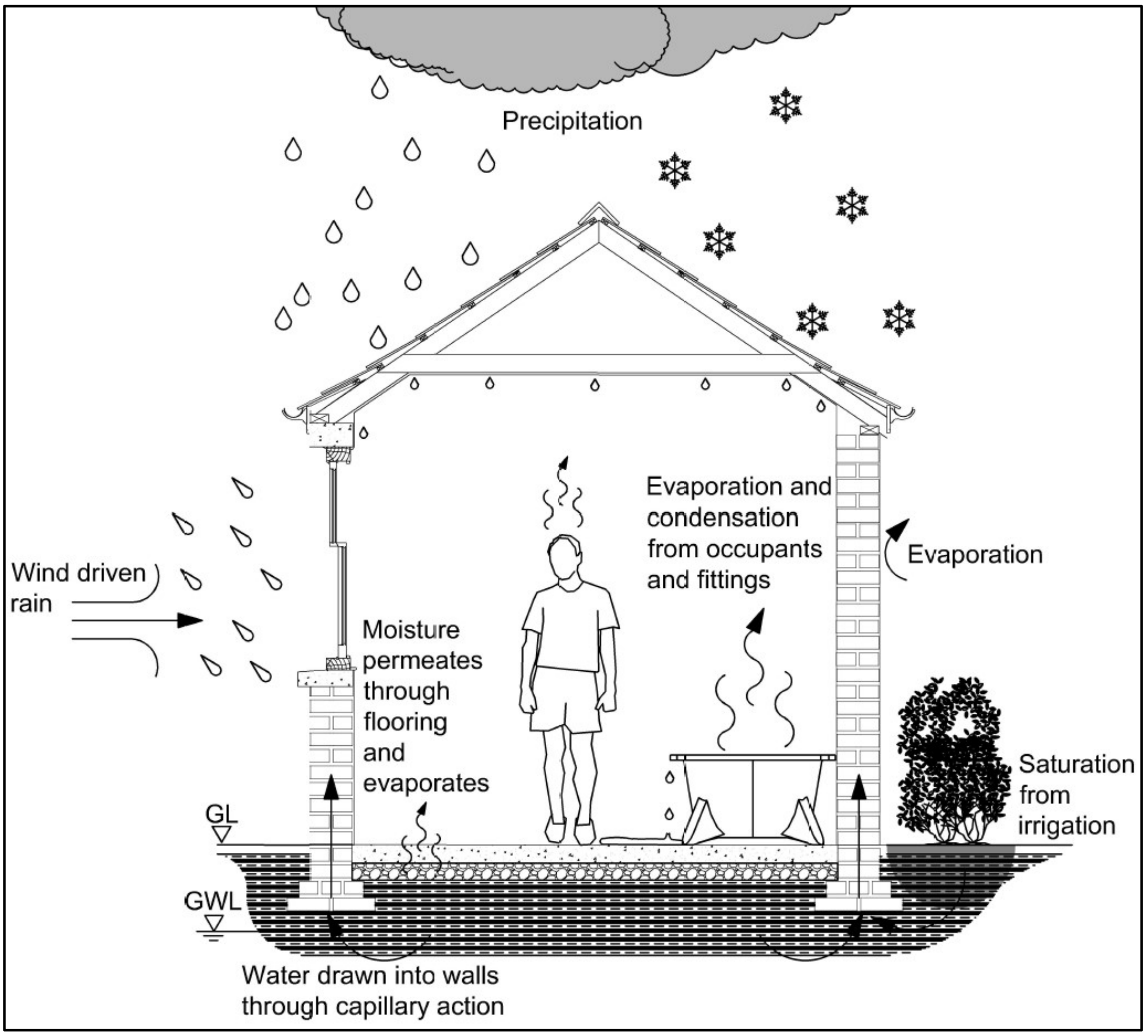

Figure 1 Moisture movement in and around buildings.

Research is being carried out at the University of Bath in collaboration with Historic England to understand the influence of floor slab material (concrete or limecrete) on soil moisture and dampness within the walls of historic buildings. Firstly, modelling was used to explore how the permeability of floor slab materials influenced local ground water flow in the liquid and vapour phases. Secondly, a suite of laboratory tests were carried out to determine the material properties of concrete and limecrete slabs and measure their comparative moisture permeation rates. Lastly, long term field measurements have been taken at two properties to investigate the *in situ* response of both soil and wall moisture levels to changes in floor materials (Briggs 2017). These measurements are ongoing. This paper focuses on the initial findings from the laboratory element of the project, outlining the experiments and comparing concrete and limecrete slabs with respect to their moisture transport properties. The laboratory tests included a modular soil-slab-air experiment and a range of material characterisation tests. The modular soil-slab-air experiment was developed for the project and was run for a period of at least four weeks per slab in order to measure moisture transfer rates. Subsequent characterisation tests were carried out in order to correlate the slab properties with the observed water movement. These tests included imaging using a scanning electron microscope (SEM), mercury intrusion porosimetry (MIP), sorptivity testing, and mechanical characterisation by compression testing.

Materials

Two materials have been tested in the modular system; concrete and limecrete. The limecrete slab was manufactured using the highest strength classification of commercially available natural hydraulic lime (NHL5). The slab mix designs are shown in Table 1.

Table 1 Material designs for concrete and limecrete slabs tested

	Limecrete	**Concrete**
Components	NHL (Roundtower NHL5) 6mm to dust aggregate Gravel	Cement 6mm to dust aggregate Gravel
Coarse:fine ratio	0.54	0.4
Binder:aggregate ratio	0.33	0.2
Water ratio	0.50	0.625
Binder:fine aggregate:coarse aggregate ratio	1.00 : 1.95 : 1.05	1.00 : 3.57 : 1.43

The concrete and limecrete were cast as circular slabs, as shown in Figure 2, to fit the modular set-up. Two bolts were cast into the slab to facilitate installation and removal. The concrete and limecrete slabs were of thickness 84mm and 86mm ±2mm respectively. They were cast to fit the apparatus, which had an internal diameter of 355mm ±1mm with a gap around the perimeter of approximately 10mm. Slabs were installed within 2-4 weeks of casting and had not completely cured.

Figure 2 Cast concrete slab prior to use in the modular slab experiment.

Experimental Set-up and Procedure

Modular Slab Experiment

The set-up for the modular slab experiment is shown in Figure 3. A galvanised steel cylinder was filled with 50mm of gravel, then 80mm of clay soil. The clay was saturated with water. Water evaporating from within the cylinder was replaced by water supplied at a constant pressure head through the use of a Mariotte bottle. The Mariotte bottle was set on scales to log the change in mass with time. A Tinytag temperature and relative humidity (RH) probe was installed at the top of the cylinder to monitor the environment at the surface. The experiment was run for a minimum of four weeks with no soil to determine the free water conditions and then with a bare soil layer for four weeks, as shown in Figure 4, to establish the evaporation rate for a bare soil condition.

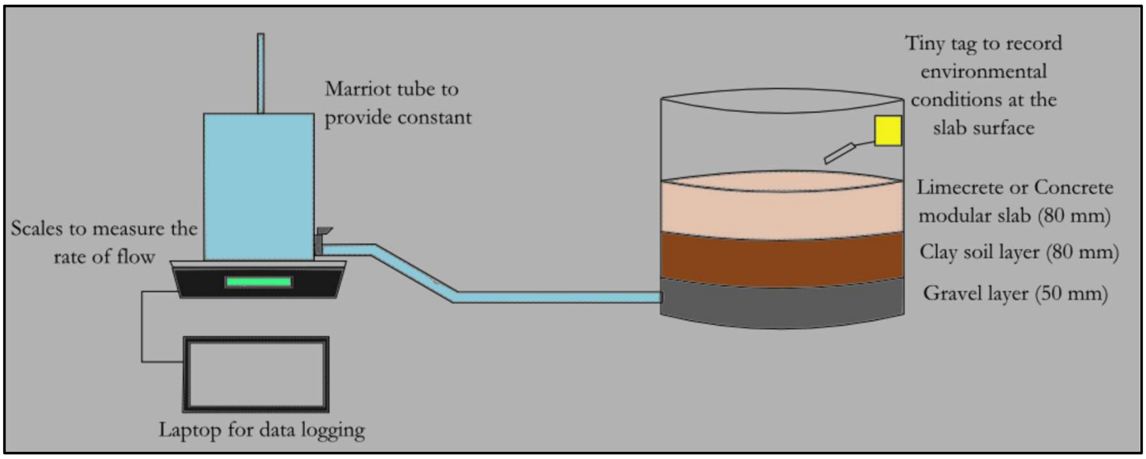

Figure 3 A diagram of the modular soil-slab-air experiment set-up.

Figure 4 Initial saturation of the bare soil surface.

The cast slabs were inserted into the cylinder directly onto the clay soil surface and sealed with silicon rubber around their perimeter. This setup excluded additional elements such as damp proof membranes (DPMs) and so does not directly replicate typical floor systems. However this enables a direct comparison of slab materials to be made without inhibiting moisture transfer to the underside of the slab. Each stage of the test was monitored for a duration of at least four weeks. The limecrete was monitored for the first 12 weeks followed by bare soil for 4 weeks and then the concrete slab for 9 weeks. Following extraction from the apparatus both slabs underwent further analysis.

SEM Imaging

Scanning electron microscopy (SEM) imaging was carried out using a JEOL SEM6480LV to reveal the microstructure and nature of the porosity. The SEM scans a focused beam of electrons on the surface which interact with the sample producing secondary electrons which are detected and the resulting signal used to produce an image. Fracture surfaces from slab samples were coated in gold prior to imaging to prevent surface charging, enabling clearer images to be taken and at higher levels of magnification. Images were taken at x100, x500, x1k, x2k, x4k, x5k, and x10k magnification.

Mercury Intrusion Porosimetry (MIP)

MIP tests provided a quantitative measure of the size distribution of the internal pores. The Pascal 140 and Pascal 440 from Thermo Scientific were both used to carry out the test. The sample is first inserted into the low pressure Pascal 140 which pressurises the mercury, forcing it into the accessible pores. As the pressure increases, the mercury enters into smaller pores. The Pascal 140 increases the pressure up to 400kPa and once the test is completed in the Pascal 140 the sample is transferred to the high pressure Pascal 440. The Pascal 440 increases the pressure up to 400MPa. The results from the 140 and 440 are then combined providing data over the entire pressure range. Plotting the pore diameter against intruded pore volume is a tool for establishing the critical length of a material. The critical length, 'R_C', is the pore diameter that corresponds to the sample's breakthrough pressure. It is considered the largest particle size that can percolate through a sample.

Compression Tests

Compression tests, carried out to BS 1015-11, elucidated the mechanical properties of the slab material. Blocks of approximate size 40mm x 40mm x 40mm (±4mm) were cut from the slab following testing and the exact measurements to the nearest mm recorded. Six samples cut from each slab were tested to failure using either the 50kN Instron 3369 or the 2000kN Automax 5 concrete compression equipment and the peak load was recorded. The peak load and applied area were then used to calculate the ultimate compressive strength of the sample. This characteristic is important as slabs require a minimum compressive strength to be suitable for use as a floor slab (NHCB 2018).

Sorptivity Tests

Sorptivity tests enabled the material's capacity to absorb water to be ascertained. This property is important as the absorption provides a supply of water to be transferred and evaporated. The tests were carried out to BS 1015-18. Samples were cut to 40mm x 40mm (±4mm) x approximately 80mm. The samples were dried in a 50°C oven until constant mass was achieved. Samples were then placed within a tray of water on supports such that the sample was immersed in approximately 10mm of water. Samples were weighed and the water height on the sample surface was measured at 10, 40, 90, 160, and 250 minutes.

Results

Water Transfer Rates

The change in mass of the mariotte bottle was recorded at one minute intervals, allowing the water (vapour) transfer rate through the slabs to be easily calculated in $gmin^{-1}$ or $gday^{-1}$. The water transfer rate represents the actual evaporation rate from the slab or soil surface, which is less than the potential evaporation rate from a free water surface (Penman 1948). The rate can be converted to ms^{-1} using equation 1,

$$E(ms^{-1}) = \frac{E(gday^{-1})}{86400 \times 10^3 \times \rho \times A} \qquad \text{Equation 1}$$

where 'E' is the water transfer rate, 'ρ' is water density for the average air temperature, and 'A' is the area of the slab at 0.088 m^2. The resulting rates are in Table 2.

Table 2 Actual evaporation rates for each testing configuration

Surface	Average E ($gmin^{-1}$)	Average E ($gday^{-1}$)	Average Temp. (°C)	ρ (kg/m^3)	Average E (ms^{-1})
Free water (gravel)	0.1708	246.0	18.1	998.6	32.39×10^{-9}
Bare clay surface	0.0754	108.6	19.4	998.3	14.31×10^{-9}

Limecrete (NHL5) slab	0.0063	9.018	20.1	998.2	1.188×10^{-9}
Concrete slab	0.0041	5.966	20.9	998.0	0.786×10^{-9}

The gravel surface had the greatest water transfer rate and had more than double the water transfer rate of the bare clay surface; this is because the clay restricted the supply of water to the surface for evaporation. The addition of a slab further restricted the supply. The limecrete slab was only marginally less restrictive than the concrete slab. For the limecrete and concrete slabs water transfer rates were smaller than the bare clay soil by 12 and 18 times respectively.

SEM Imaging

The x10k SEM images of the limecrete and concrete are presented in Figure 5 and 6 respectively. Calcium Silicate Hydrate (C-S-H) can be seen in both samples with a greater number of larger needle-like structures in the NHL5 limecrete sample.

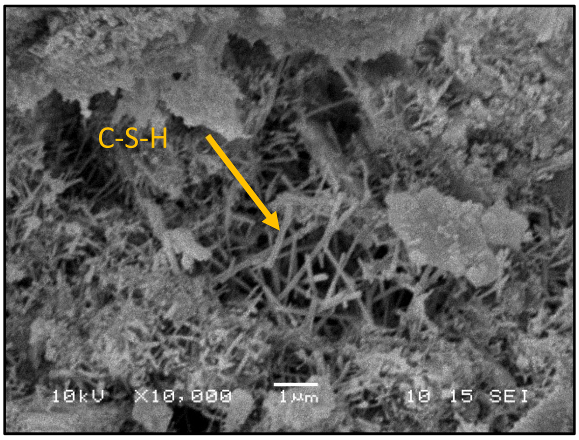

Figure 5 SEM image of the NHL5 limecrete sample showing signs of formed calcium silicate hydrate (C-S-H).

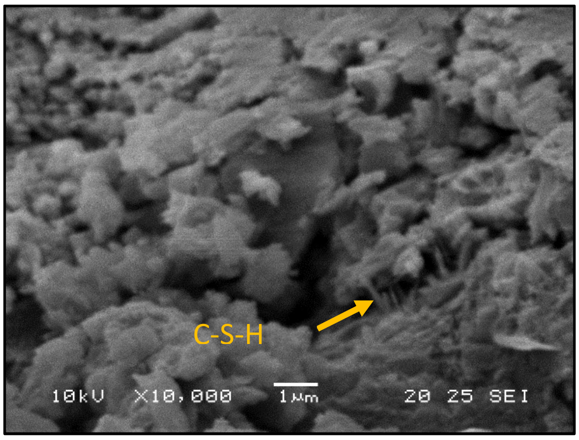

Figure 6 SEM image of the concrete sample showing signs of formed C-S-H.

Mercury Intrusion Porosimetry (MIP)

MIP results are provided in Table 3 and Figure 7. The critical length 'R_C' for both materials lie within the capillary region; for limecrete it was circa 50nm and the concrete had a bimodal distribution with two peaks at around 75nm and 300nm. For concrete the largest pore diameter of 300nm is the critical length and represents the largest size particle that can percolate through the sample. Through comparing the limecrete and concrete plots in Figure 7 it can be seen that the limecrete had a greater pore volume, as is confirmed by the total pore volume values given in Table 3.

Table 3 MIP results for limecrete and concrete

Case	Bulk Density (g/cm^3)	Total Pore Volume (cm^3/g)	Total Pore Area (m^2/g)	Porosity by Hg Intrusion (%)	Average Pore Diameter (nm)
Limecrete	2.1319	0.0915	10.236	19.51	35.75
Concrete	2.2096	0.0665	6.716	14.68	39.58

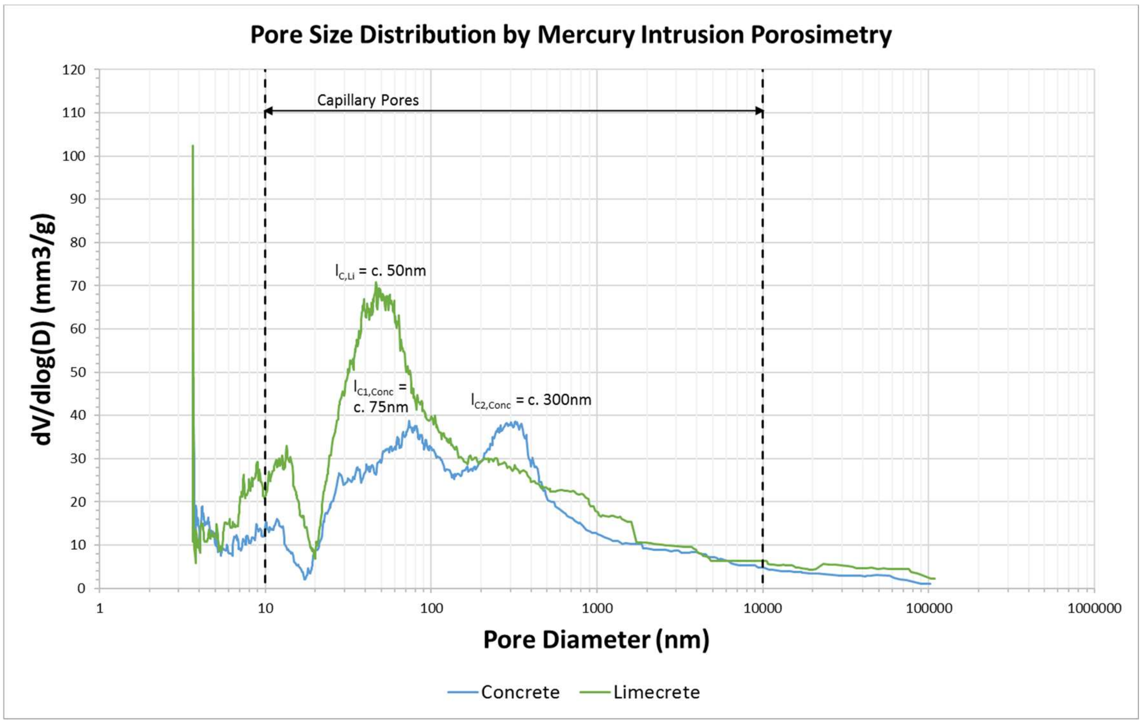

Figure 7 Plot of pore volume measured by MIP, with pore diameter for the limecrete and concrete samples.

Compressive Strength

The results for the compressive tests are given in Table 4. The Limecrete had an average compressive strength of 14.56MPa. The concrete samples exhibited a greater compressive strength of 25.18MPa, however the concrete samples were less consistent, as demonstrated by the larger standard deviation. Any samples that exceeded the 50kN load capacity of the Instron 3369 were tested using the Automax 5.

Table 4 Compressive strengths for limecrete and concrete samples

Material	Sample	Instrument Capacity	Ultimate Compressive Strength σ_{ULT} (MPa)	Mean Compressive Strength (MPa)	Standard Deviation (MPa)
Limecrete	L1	50kN	15.22	14.56	1.15
	L2a	50kN	13.13		
	L3	50kN	15.51		
	L4	50kN	15.04		
	L5	50kN	12.80		
	L6	50kN	15.69		
Concrete	C1a	2000kN	24.02	25.18	4.90
	C2	2000kN	21.05		
	C3	2000kN	21.86		
	C4	50kN	20.32		
	C5	50kN	31.99		
	C6	50kN	31.85		

Sorptivity

The coefficient of water absorption was calculated for each sample using the equation

$$\mathrm{C} = 0.1\frac{m_{90}-m_{10}}{A\sqrt{t}} \qquad \text{Equation 2}$$

where 'C' is the coefficient of water absorption in $kgm^{-2}min^{0.5}$, 'm_{90}' is the sample mass at 90 minutes in kg, 'm_{10}' is the sample mass at 10 minutes in kg, 'A' is the cross-sectional area in m^2, and 't' is the time in minutes. Table 5 shows the sorptivity results for two samples of concrete and one sample of limecrete.

Table 5 Sorptivity coefficients for limecrete and concrete

Sample	Material	Mass at 10s, m_{10} (g)	Mass at 90s, m_{90} (g)	Coefficient of water absorption ($kgm^{-2}min^{0.5}$)
L3	Limecrete	290.51	294.06	0.023
C2	Concrete	269.60	271.36	0.013
C3	Concrete	299.38	300.93	0.010

Discussion

Water Transfer Rate

Models of ground and wall moisture flow have been developed at the University of Bath. These suggest that the floor slab material will affect the supply of water to the wall base and hence the water available for transfer through the wall. The initial laboratory results showed that the clay had an influence on the rate of water transfer and evaporation and that the presence of a slab further impeded water transfer. The two slab materials tested to date, NHL5-based limecrete and concrete, exhibited similar water transfer rates with limecrete being marginally more effective at moisture transfer. Further testing including alternative slab compositions and capillary breaks is proposed to ascertain whether the modular slab experiment supports the findings from the model. The authors are also undertaking *in situ* long term monitoring of full scale trials at two historic properties to assess what impact slabs have on wall and soil moisture.

SEM Imaging

The needle-like structures shown in Figure 5 and 6 are calcium-silicate-hydrate (C-S-H) formed from hydrated silicates in both the NHL and cement. In NHLs they grow during the initial hydration phase of hardening, enhancing the material's strength. The morphology of the C-S-H structures in the concrete sample are more consolidated compared to that in the NHL resulting in a denser structure. This is demonstrated by the smaller number of voids visible in Figure 6 than in Figure 5 and the higher bulk density and lower pore volume values for concrete in Table 3.

Mercury Intrusion Porosimetry (MIP)

The bulk density and pore volume values for the concrete showed that it is more dense than the limecrete. Whilst the concrete had a larger critical length and a greater average pore diameter, the limecrete had a greater pore volume, most of which lies within the capillary region. It is this accessible interconnected pore structure that contributes to greater water transfer rates through the limecrete.

Compressive Strength

The compressive strength for the concrete was almost double that of the limecrete. The minimum compressive strength of the limecrete was 12.80MPa which is adequate for classification as a GEN 1 concrete. GEN 1 concrete typically has a compressive strength of 10MPa and the NHBC class this as suitable for use in unreinforced house floors with permanent finishes (Mister Concrete n.d.; EasyMix Concrete UK Ltd n.d.; NHCB 2018). Floor slab compressive strength is only one indication of appropriateness for use and further testing is required before slab mixes are adopted. For example durability testing is required to assess the slab resistance to abrasion, freeze-thaw, and chemical and salt attack.

Sorptivity

The sorptivity of the limecrete was approximately double the concrete's sorptivity. This suggests that the limecrete uptakes water quicker than the concrete, providing more water supply for evaporation at the surface, enabling higher water transfer rates. Further sorptivity testing is proposed to validate these results and compare these slab materials with those used in future tests.

Conclusions

The water transfer rates derived from the bespoke modular soil-slab-air apparatus showed that soil restricts the water supply to the surface for evaporation, and the addition of a slab restricts the supply further. The water transfer rate of the sample slabs was affected by the sorptivity of the material and the presence of an interconnected pore structure. The NHL5 limecrete slab was found to have a greater sorptivity and pore volume than the concrete slab, and hence it had a greater water transfer rate when tested in the soil-slab-air apparatus. Preliminary results obtained from modelling and laboratory tests suggest that NHL5-based limecrete was marginally more effective than a concrete slab in transferring moisture. However, this has yet to be verified with further testing of different slab compositions, by the long-term monitoring of *in situ* installations, and through representative slab tests including typical construction details such as capillary breaks. Following the successful demonstration of the apparatus detailed in this article, further floor slab systems will be tested to provide a representative range of moisture transport characteristics. Additional studies will explore construction variations such as the inclusion of cracks and construction joints.

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